A Transimpedance Amplifier for Remotely Located Quartz Tuning Forks

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The cable capacitance in cryogenic and high vacuum applications of quartz tuning forks imposes severe constraints on the bandwidth and noise performance of the measurement. We present a single stage low noise transimpedance amplifier with a bandwidth exceeding 1 MHz and provide an in-depth analysis of the dependence of the amplifier parameters on the cable capacitance.

Quartz tuning forks (QTF) have proven to be a versatile tool in optical near-field microscopy[1], in scanning probe microscopy[2], in studies of the quantum liquids[3], in mass sensing in biological systems[4], in magnetometry[5], and in low temperature thermometry[6]. Their popularity stems from their high quality factor and from the possibility of electrical excitation and detection. In a growing number of cryogenic and high vacuum applications the QTF cannot be located close the the measurement electronics and, therefore, cables with significant capacitances are often used to connect them[6–14].

QTFs operate in the 20-150 kHz frequency range but novel devices, called needle oscillators, may resonate at frequencies as high as 1 MHz[15–17]. At such frequencies and in the presence of considerable cable capacitances the preferred measurement circuits employ current detection with a transimpedance amplifier (TIA). Many applications require small amplitude oscillations and, therefore, benefit from low noise amplification.

Large cable capacitances have a negative impact on the bandwidth and noise performance of TIAs. For low temperature QTF applications cryogenic TIAs were developed which are placed in close proximity to the QTF and, therefore, reduce the cable capacitance[17–22]. Such amplifiers, however, present significant challenges as careful selection of the active component and extra wiring for biasing are needed. In addition, dissipation in the active component is often undesirable. In lack of detailed noise analysis, the conditions under which cryogenic TIAs are beneficial remain unknown.

We present a single stage wide band TIA which operates at room temperature and which is designed for low noise measurements of QTFs in applications requiring long cables. We present a careful analysis of the frequency response and noise performance and show that they remain virtually unaffected by the 180 pF cable capacitance of our setup. For QTFs at room temperature we find that the amplifier noise is negligible as compared to the intrinsic thermal noise of the QTF. In contrast, the amplifier noise prevails for QTFs at liquid helium temperatures. To our surprise, the dominant noise term is due to the voltage noise rather than the current noise of the TIA. The overall noise performance of our TIA is either superior to or similar to that of cryogenic TIAs[18,20–22].

The circuit of our TIA is shown in Fig.1a. We make use of the low bias current OPA657 op-amp from Texas
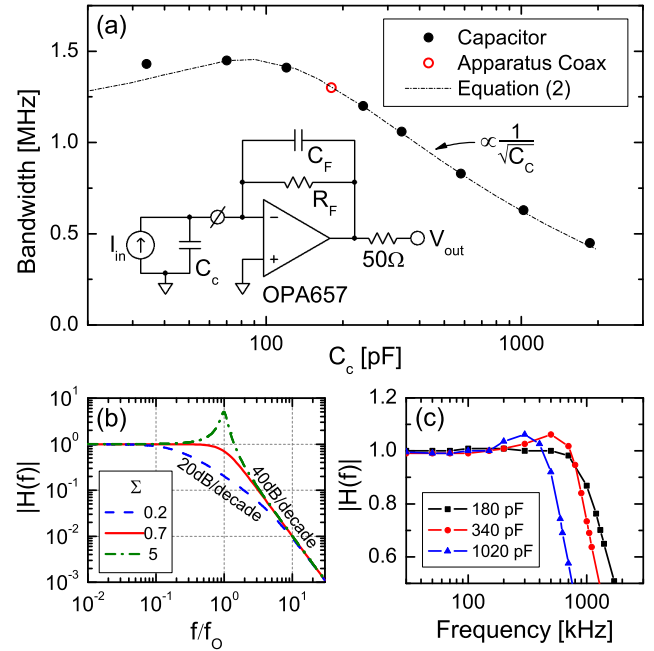

FIG. 1. Amplifier bandwidth for several values of the input capacitance (panel a). Dots are measured values and the continuous line is the prediction of Eq.2. The three qualitatively different frequency responses of TIAs (panel b). The measured frequency response of our TIA for three different cable capacitances C_C (panel c).

Instruments. The transimpedance gain is set by the $R_F = 1$ MΩ feedback resistor. This resistor has a size 0805 surface mount packaging which, together with the circuit board, adds a small parasitic capacitance $C_F \sim 0.14$ pF. The capacitor at the input C_C represents either a fixed capacitor used to characterize the circuit or the 180 pF coaxial cable which is part of our cryostat. The circuit also contains a 50Ω output resistor necessary to inhibit oscillations for capacitive loads and customary pairs of bypass capacitors of 10 nF and 10 μF. Circuit components, with the exception of R_F mounted on the back side of the circuit board, are visible in Fig.2a.

The frequency response of TIAs is quite different from

that of the more widely used voltage amplifiers. The latter have a single-pole response similar to that of a low pass RC filter. In contrast, TIAs have a more complicated response. Using a single-pole model $A(f) = A_{OL}f_A/(jf + f_A)$ for the op-amp, the magnitude of the dimensionless transfer function $|H(f)|$ for a feedback TIA, such as ours, is[23]

$$|H(f)| = \left| \frac{v_{out}}{R_F i_{in}} \right| = \frac{f_0^2}{\sqrt{(f^2 - f_0^2)^2 + f^2 f_0^2/\Sigma^2}}. \quad (1)$$

Here A_{OL} is the dc open loop gain and f_A is corner frequency of the open loop gain of the op-amp. For large A_{OL} and large cable capacitances $C_C \gg C_F$ the constants in the above equation relate to the circuit parameters as follows[23] $f_0 = \sqrt{A_{OL}f_A/2\pi R_F C_C}$ and $f_0/\Sigma = f_A(1 + A_{OL}C_F/C_C)$. The bandwidth f_{3dB} of the circuit can be expressed as

$$f_{3dB}^2 = f_0^2 \left[\sqrt{(1 - 1/2\Sigma^2)^2 + 1} + (1 - 1/2\Sigma^2) \right]. \quad (2)$$

It is often unappreciated that the TIA transfer function has three qualitatively distinct behaviors. As seen in Fig.1b, for $\Sigma > 0.70$ there is a peak in the response at $f = f_0$ followed by a 40 dB/decade roll-off at higher frequencies. This peaking gain may drive the circuit to saturation and it is commonly avoided by increasing C_F[23]. For $\Sigma \ll 0.70$, the frequency response is flat up to Σf_0, it has a 20 dB/decade roll-off for $f_0\Sigma \lesssim f \lesssim f_0/\Sigma$, and it has a 40 dB/decade roll-off at higher frequencies. It can be shown that in the 20 dB/decade region the circuit works as a charge amplifier[14]. Finally, for the limiting case of $\Sigma = 0.70$ one obtains a maximally flat response followed by a 40 dB/decade roll-off at higher frequencies. In this case the bandwidth can be approximated as[23]

$$f_{3dB} \simeq \sqrt{A_{OL}f_A/2\pi R_F C_C}. \quad (3)$$

Here $A_{OL}f_A$ is the familiar gain bandwidth product GBP of the op-amp and the OPA657 was chosen because of the exceptionally high 1.6 GHz value of this product.

In Fig.1c we show the measured frequency response of our TIA for different C_C. We find that for $C_C = 180$ pF of our coax the frequency response is nearly maximally flat and the bandwidth is exceptionally large 1.3 MHz. This value agrees well with the prediction of Eq.3. For C_C up to 2 nF the bandwidth clearly remains wider than 32 kHz, the resonant frequency of the most common QTFs. In Fig.1a we plot the bandwidth extracted from our measurements and that expected from Eq.2. When using the parameters $A_{OL} = 5 \times 10^3$ and $f_A = 0.32$ MHz of the OPA657, the two compare favorably for a wide range of C_C. Furthermore, since for our TIA the parameter Σ is close to 0.70 when $C_C \gtrsim 200$ pF, for this range of capacitances Eq.3 predicts a bandwidth that scales approximately as $1/\sqrt{C_C}$.

QTFs are modeled as a series resonant LCR circuit connected in parallel with an additional capacitance[7]. However, near the resonance the approximation of a
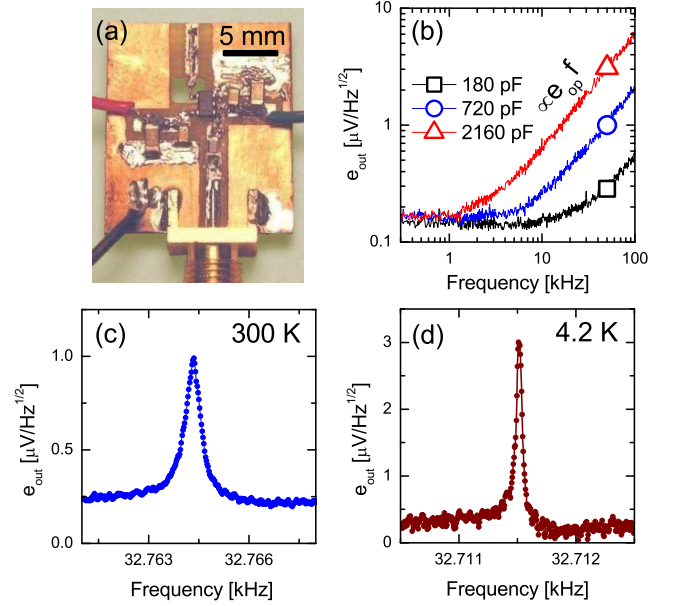

FIG. 2. A photo of the circuit layout (panel a). The amplifier output noise at three different input capacitances C_C (panel b). The amplifier output noise at 300 K (panel c) and 4.2 K (panel d) when a QTF is connected to its input.

purely resistive impedance R_{QTF} works well[24]. Our TIA can be conveniently used to determine R_{QTF} of the Citizen CFS308 QTF when using a 10 mV excitation. During the measurements the QTF remained in its vacuum seal canister. The obtained R_{QTF} values at 300 K and 4.2 K are listed in Table.I.

In the following we discuss the noise analysis of our TIA with a QTF connected to its input. In order to determine the dominant term in the power spectrum density e_{out} measured at the output of the TIA, it is useful to separate contributions due to the QTF and to the TIA itself. The former consists of the thermal noise $\sqrt{4k_B T_{QTF}/R_{QTF}}$ at the resonant frequency of the QTF. We used k_B for Boltzmann's constant and T_{QTF} for the temperature of the QTF. The amplifier noise i_{amp} has four major contributions: one due to the current noise of the op-amp i_{op}, one due to the voltage noise of the op-amp e_{op}, one due to the presence of the capacitance C_C at the input of the TIA, and one due to the thermal fluctuations in the feedback resistor R_F. Since noises add in quadrature, the amplifier noise can be expressed as[23]

$$i_{amp}^2 = i_{op}^2 + (e_{op}/R_{QTF})^2 + (2\pi e_{op}fC_C)^2 + 4k_B T_F/R_F. \quad (4)$$

Adding to this the thermal noise of the QTF we find the noise at the output of the TIA is

$$e_{out}^2 = R_F^2 \left(4k_B T_{QTF}/R_{QTF} + i_{amp}^2 \right). \quad (5)$$

By establishing the dominant term in e_{out} we can identify possibilities for lowering the noise levels and, further-

T_{QTF} [K]	R_{QTF} [kΩ]	$\sqrt{4k_B T_{QTF}/R_{QTF}}$	e_{op}/R_{QTF}	$2\pi f e_{op} C_C$	$\sqrt{4k_B T_F/R_F}$	e_{out} [μV/$\sqrt{\text{Hz}}$]
300	17	0.99	0.28	0.18	0.13	1.0
4.2	1.7	0.37	2.8	0.18	0.13	2.8

TABLE I. The parameters of the QTF, the contributions of different noise terms, and the prediction for the output noise e_{out} of the TIA. Noise estimations are done at the resonance frequency f of the QTF and using $C_C = 180$ pF of our cable. Where not labeled, noise terms are measured in units of pA/$\sqrt{\text{Hz}}$.

more, we may compare the noise performance of various TIAs.

The noise parameters of the op-amp i_{op} and e_{op} may be read from the op-amp specification sheet. However, the residues of the soldering flux left on the circuit board may cause excess noise. To avoid this, we opened a hole in the circuit board near the inverting input which is visible in Fig.2a. To estimate e_{op} we measured e_{out} with three different capacitances connected to the input in the regime in which the frequency dependent third term in Eq.4 becomes significant. As seen in Fig.2b, this occurs at high frequencies and the data is consistent with the $e_{op} = 4.8$ nV/$\sqrt{\text{Hz}}$ specified for the OPA657.

With the measured e_{op} we calculate the expected noise at the output e_{out} at the resonant frequency of the QTF. The values at two different temperatures of our QTF are listed in Table.I. The extremely low $i_{op} = 1.3$ fA/$\sqrt{\text{Hz}}$ of the OPA657 can be safely neglected. Measured noise data at 300 K and 4.2 K are shown in Fig.2c and Fig.2d, respectively. We find that the measured peak values of e_{out} are in good agreement with the estimations from Table.I and, hence, our noise model is satisfactory.

We note that because of the LCR series circuit model of the QTF, at resonance e_{out} exhibits a peak[25] such as the ones in Fig.2. However, such a peak could be either due to the thermal noise of the QTF or due to amplifier noise, depending on which one dominates. By inspecting the noise estimations listed in Table.I, we find that when the QTF is at room temperature the amplifier noise is negligible and, therefore, the peak in Fig.2c is due to the thermal noise of the QTF[14,25]. Any attempts to lower the noise of the TIA are unnecessary in this case. In contrast, when the QTF is at the temperature of liquid helium, the peak in e_{out} shown in Fig.2d is dominated by the amplifier noise i_{amp}. Numbers from Table.I show that virtually all the noise comes from the e_{op}/R_{QTF} term. We thus find that for low noise measurements of cold QTFs the voltage noise of the TIA rather than its current noise has to be minimized. For our QTF the capacitance-dependent $2\pi f e_{op} C_C$ term remains negligible both at 300 K and at 4.2 K.

We compare our room temperature TIA to cryogenic TIAs[18–22]. One TIA[18] has 5 times the noise for a similar R_{QTF}, hence we infer a voltage noise which is 5 times larger than ours. Another TIA[21] has 26pA/$\sqrt{\text{Hz}}$ at 55 kHz which is about 80 times larger than ours at the same frequency. The TIA in Ref.[22] has 100nV/$\sqrt{\text{Hz}}$ at room temperature and most likely remains much larger than ours when cooled. The TIA which uses a JFET

transistor as a first stage[20] has 3 nV/$\sqrt{\text{Hz}}$ which is 37% smaller than ours. In the absence of sufficient data, we are unable to compare our results to those in Ref.[19]. We find, therefore, that there is very little or no improvement in the noise performance of cryogenic TIA as compared to ours. For needle oscillators of high frequency[17], however, $2\pi f e_{op} C_C$ will be significant, hence important improvements result when reducing C_C. Finally we note that a recently published room temperature TIA is expected to have a low voltage noise near 1 nV/$\sqrt{\text{Hz}}$[26]. This is, however, not a single stage but a discreet JFET/op-amp hybrid circuit and, therefore, it is considerably more difficult to be built than ours.

To summarize, we built a low noise single stage TIA intended to be used for QTF measurements. We have demonstrated a very large bandwidth of 1.3 MHz at 180 pF cable capacitance. We have provided a detailed noise analysis and found that our amplifier adds negligible amount of noise when the QTF is at room temperature. For cold QTF, however, the voltage noise of the op-amp becomes important and we provided a useful way to measure it. The noise due to the cable capacitance is found to be negligibly small. This work was supported by the DOE BES under contract no. de-sc0006671.

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